Conference “The Milky Way Halo - Stars & Gas”, AIfA Bonn, 2007, Poster 18

Stellar Effective Temperatures Derived from the Analysis of Balmer Line Profiles in 3D Metal-Poor Models

N. T. Behara[1], H.-G. Ludwig[1], P. Bonifacio[1], & M. Steffen[2]

[1]CIFIST, Observatoire de Paris-Meudon, 92195 Meudon Cedex, France

[2]Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

natalie.behara@obspm.fr

Summary

Synthetic Balmer line profiles computed using 3D hydrodynamical model atmospheres have been compared differentially to 1D models of varying mixing-length. Hα was found to become much less sensitive to temperature in metal-poor stars, and the profiles of Hβ and Hγ were found to vary strongly with mixing-length. For α = 0.5, the 3D models gave cooler effective temperatures using Hα by 100-220 K for metal-poor stars, and by 50 K for solar metallicity.

Introduction

One of the primary methods used in determining the effective temperature of a cool star involves the comparison of synthetic to observed Balmer line profiles. Temperature determinations are based mostly on the Hα line, since it is formed above the convective zone in solar metallicity stars, and is therefore nearly insensitive to the mixing-length. However, in the case of metal-poor stars, where the convective zone reaches further out in the atmosphere, the Hα line may be affected, and as a consequence, may not be completely insensitive to the mixing-length.

Synthetic spectra computed using 3D hydrodynamical model atmospheres and 3D line formation have the property that they are independent of free parameters inherent to 1D models, such as the mixing-length. By comparing differentially 1D to 3D Balmer line profiles for a range of metallicities in cool stars, we explore the magnitude of the 3D temperature corrections for these stars.

Model Atmospheres

The 3D atmosphere models presented here were computed with CO^{5}BOLD, a 3D radiation hydrodynamics code designed to model stellar convection (see Freytag et al. 2002 or Wedemeyer et al. 2004 for details). The integration of the equations of hydrodynamics is based on a conservative finite volume approach using an approximate Riemann solver of Roe type together with a *van Leer* reconstruction scheme. The Roe solver was modified to handle an external gravity field and an arbitrary tabulated equation of state (EOS). We use a realistic EOS table specific to the chosen metallicity accounting for partial ionization of hydrogen and helium (as well as H_2 molecule formation).

The 3D non-local radiative transfer is solved on a system of long rays, employing a modified Feautrier scheme. The wavelength dependence of the radiation field is treated by a multi-group approach (Nordlund 1982) employing realistic MARCS based opacities. Strict LTE is assumed (no scattering), and radiation pressure is ignored.

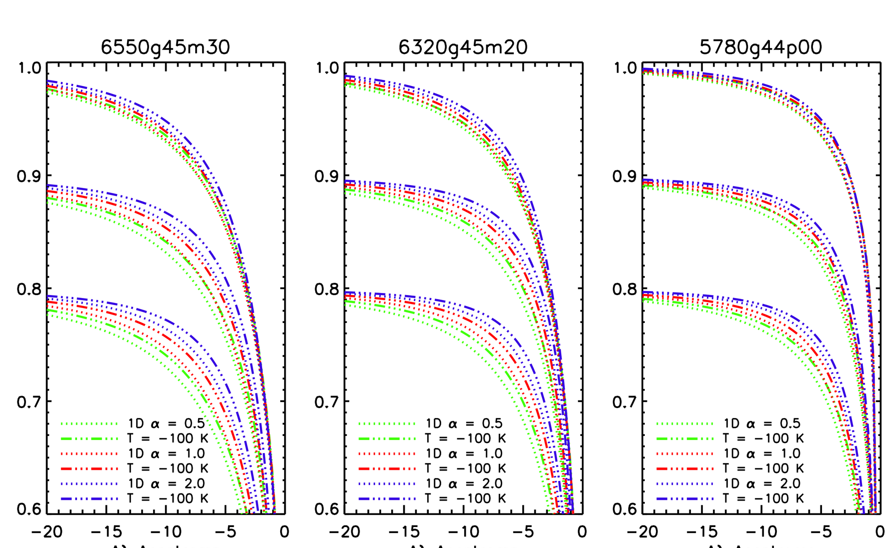
The simulations are performed on a Cartesian grid with variable cell size in the vertical direction. We apply periodic lateral, as well as open top and bottom boundary conditions.

CO^{5}BOLD radiation-hydrodynamics model atmospheres: $T_{\rm eff}$ is the effective temperature, $\Delta T_{\rm eff,rms}$ the RMS fluctuations around the average $T_{\rm eff}$, $\log g$ the gravitational acceleration, [M/H] the metallicity, X × Y × Z the size of the computational box, $N_{\rm x} \times N_{\rm y} \times N_{\rm z}$ the number of grid points, $N_{\rm obm}$ the number of frequency bands considered in the solution of the radiative transfer equation, $N_{\rm snap}$ the number of snapshots considered in the spectral synthesis calculations, t the time interval covered by the snapshots, and “Modelcode” an internal identifier of the model sequence.

$T_{\rm eff}$	$\Delta T_{\rm eff,rms}$	log g	[M/H]	X × Y × Z [Mm]	$N_{\rm x} \times N_{\rm y} \times N_{\rm z}$	$N_{\rm obm}$	$N_{\rm snap}$	t [s]	Modelcode
5779	13	4.44	0.0	5.60x5.60x2.25	140x140x150	5	25	6000	d3gt57g44n57
5924	7	4.5	-3.0	6.02x6.02x3.78	140x140x150	6	19	9500	d3t59g45mm30n01
6324	13	4.5	-2.0	7.00x7.00x3.95	140x140x150	6	10	9600	d3t63g45mm20n01
6556	14	4.5	-3.0	8.40x8.40x3.96	140x140x150	6	12	2400	d3t65g45mm30n01
5505	15	3.5	-2.0	49.0x49.0x35.3	140x140x150	6	20	48000	d3t55g35mm20n01

The 1D atmospheres are homogeneous hydrostatic models, and assume plane-parallel geometry. The same equation of state and opacities as in CO^{5}BOLD are employed, allowing a direct comparison with the 3D models with the exception of the free parameters – mixing-length and microturbulence.

Mixing Length Parameter



The convective energy transport in a 1D atmosphere model is characterized by the mixing-length, l, in units of the atmospheric pressure scale height H_p. The choice of the parameter $\alpha = l/H_p$ depends on the details of the mixing-length theory used. The 1D models presented use the Mihalas (1978) formulation.

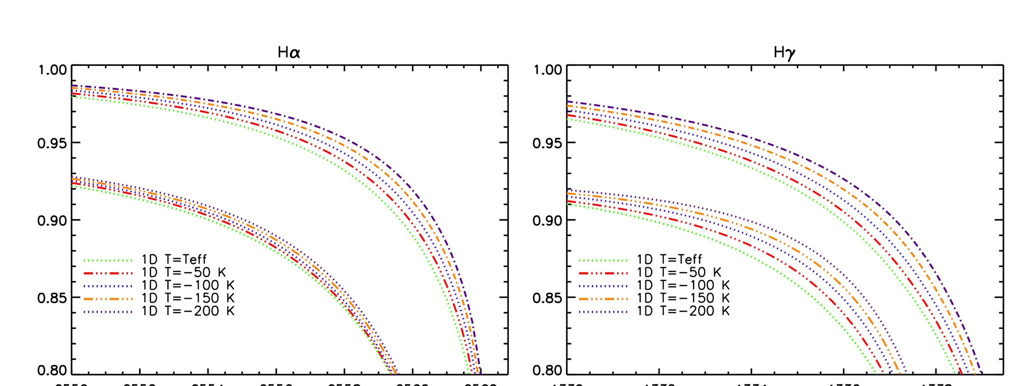
The choice of α modifies the line profiles significantly, although it is generally assumed that Hα is hardly affected by this parameter. The plots on the left show the behaviour of the line profiles of Hα (top), Hβ (middle) and Hγ (bottom) with various values of α for atmospheres with metallicities of –3.0, –2.0 and solar, and $T_{\rm eff}$ = 6550, 6320 and 5870 K, respectively.

As expected, at solar metallicities the Hα profile is not very sensitive to the choice of α. However, as the metallicity of the atmosphere is decreased, this is no longer the case. Models with temperatures cooler by 100 K have been overplotted on the figure. In the case of the star with [M/H] = –2.0, a change in α from 0.5 to 1.0 corresponds to a change in temperature of nearly 100 K, while a change in α from 1.0 to 2.0 translates to a change in effective temperature of over 100 K.

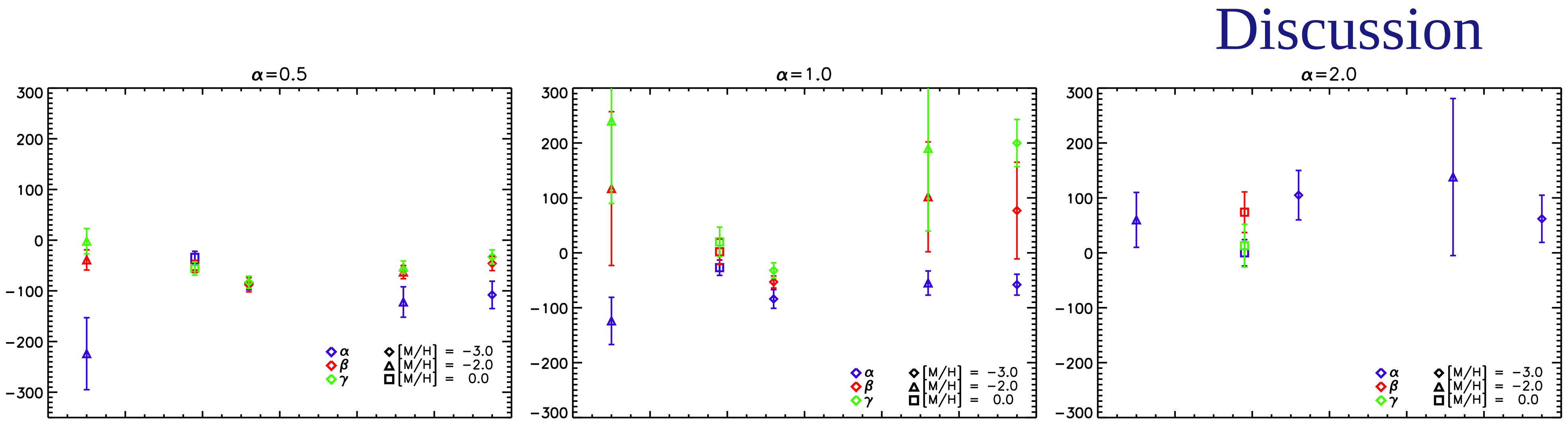
Temperature Sensitivity of Hα

The basic justification in using Hα as a temperature indicator is that the wings of the line are strongly temperature sensitive. At low metallicity, the sensitivity of Hα to temperature is quite reduced compared to the strong sensitivity of the line at solar metallicity. In comparison, the higher series member Hγ shows a much higher sensitivity. Therefore, in a temperature analysis of metal-poor atmospheres, more weight should be place on higher series members.

The variation of the Balmer line profile with effective temperature, calculated using 1D models with a fixed mixing-length of α = 0.5 is shown on the left. A similar comparison using the Hγ line is shown on the right. The top profile shows the solar metallicity models with temperatures ranging from 5580 K (top) to 5780 K (bottom). The lower profile shows models with log g = 4.5, [M/H] = –3.0, and temperatures ranging from 5720 K to 5920 K. The profiles have been offset for easy comparison.



Discussion



The three panels show temperature differences (1D – 3D) using 1D models with α = 0.5, α = 1.0 and α = 2.0, for Hα, Hβ, and Hγ. Five models are presented: T = 5500 K / log g = 3.5 / [M/H] = –2.0, solar, 5920/4.5/–3.0, 6320/4.5/–2.0, and 6550/4.5/–3.0. For α = 2.0, the Hβ and Hγ lines of the metal-poor stars were excluded from the fits, as the line wings could not be reproduced at such a large value of α.

Temperatures are obtained by fitting 1D to 3D model profiles, and solving for the minimum RMS deviation between the models. The uncertainties overplotted are indicative of the sensitivity of the profiles to temperature. For example, as shown in the figure above (left), the Hα line for the model 5920/4.5/–3.0 is quite insensitive to changes in temperature, which would translate into a large uncertainty if noise were present in the data.

These results suggest that fits of 1D models with [M/H] = 0.0 give temperatures within ± 50 K of the 3D model, independent of the mixing-length parameter for Hα, Hβ and Hγ. The smallest dispersion in $T_{\rm eff}$ from all series members occurs when α = 0.5, confirming the result of Fuhrmann et al. (1993). When considering observations, the absolute deviation would hinge on the broadening theory.

For [M/H] =–2.0 and –3.0, the following are apparent:

- The profiles of Hβ and Hγ vary strongly with α.
- Hα becomes much less sensitive to temperature.
- The smallest dispersion in $T_{\rm eff}$ occurs when α = 0.5, although Hα values are generally much cooler than the other series members by $\sim$ 200K to 70K, with the exception of 5920/4.5/–3.0 where differences of less than 5K are found between all series members.

Therefore, when determining temperatures for these stars using 1D models, care should be taken to select the correct α, and more weight should be placed on the higher series members in order to obtain correct stellar temperatures.

In the context of abundance measurements, for lithium, in F-dwarfs a ΔT $\approx$ 100 K translates into approximately ΔA(Li) = 0.06 dex, and may possibly have implications in the slope of the Li-plateau. Work is underway to investigate any corresponding colour variations.

References

Freytag B., Steffen M., Dorch B., 2002, AN, 323, 213
Fuhrmann, K., Axer, M., Gehren, T., 1993, A&A, 271, 451
Mihalas D., 1978. ’Stellar Atmospheres’, W.H.Freeman & Co., San Francisco
Nordlund Å., 1982, A&A 107, 1
Wedemeyer S., Freytag B., Steffen M., Ludwig H.-G., Holweger H., 2004, A&A 414, 1121